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INVESTIGATION OF MIXERS OF THE COMBUSTION CHAMBER OF GAS AND STEAM-GAS TURBINES

by

I. B. Palatnik and D. Zh. Temirbayev

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INVESTIGATION OF MIXERS OF THE COMBUSTION CHAMBER OF GAS AND STEAM-GAS TURBINES

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ABSTRACT: The results of calculations and an experimental study of the gas mixing process in mixers of gas turbine combustion chamber models are reported. Expressions derived by Yu. V. Ivanov (see Energomashinostroyeniye, 1958, No. 11) in a study of the propagation of single streams and stream systems in a transverse homogeneous flow were employed in evolving a program for calculating the mixing process. An example is given of calculations for a combustion chamber mixer. Tests were made on a mixer model to verify the calculation method. Cold air fed in a stream was mixed with the products of natural gas combustion passing through a cylindrical mixer. Velocity and temperature fields were measured at various cross sections of the mixer. Measurements were made at various postions of the stream in the cross section of the mixer. Test results were compared with calculated data. Bibl. with 6 titles. Yu. Dityakin. English translation: 14 pages

U. S. BOARD ON GEOGRAPHIC NAMES TRANSLITERATION SYSTEM

Block	Italic	Transliteration	Block	Italic	Transliteration
А а	*А а*	A, a	Р р	*Р р*	R, r
Б б	*Б б*	B, b	С с	*С с*	S, s
В в	*В в*	V, v	Т т	*Т т*	T, t
Г г	*Г г*	G, g	У у	*У у*	U, u
Д д	*Д д*	D, d	Ф ф	*Ф ф*	F, f
Е е	*Е е*	Ye, ye; E, e*	Х х	*Х х*	Kh, kh
Ж ж	*Ж ж*	Zh, zh	Ц ц	*Ц ц*	Ts, ts
З з	*З з*	Z, z	Ч ч	*Ч ч*	Ch, ch
И и	*И и*	I, i	Ш ш	*Ш ш*	Sh, sh
Й й	*Й й*	Y, y	Щ щ	*Щ щ*	Shch, shch
К к	*К к*	K, k	Ъ ъ	*Ъ ъ*	"
Л л	*Л л*	L, l	Ы ы	*Ы ы*	Y, y
М м	*М м*	M, m	Ь ь	*Ь ь*	'
Н н	*Н н*	N, n	Э э	*Э э*	E, e
О о	*О о*	O, o	Ю ю	*Ю ю*	Yu, yu
П п	*П п*	P, p	Я я	*Я я*	Ya, ya

* ye initially, after vowels, and after ъ, ь; e elsewhere. When written as ё in Russian, transliterate as yё or ё. The use of diacritical marks is preferred, but such marks may be omitted when expediency dictates.

FOLLOWING ARE THE CORRESPONDING RUSSIAN AND ENGLISH DESIGNATIONS OF THE TRIGONOMETRIC FUNCTIONS

Russian	English
sin	sin
cos	cos
tg	tan
ctg	cot
sec	sec
cosec	csc
sh	sinh
ch	cosh
th	tanh
cth	coth
sch	sech
csch	csch
arc sin	$\sin^{-1}$
arc cos	$\cos^{-1}$
arc tg	$\tan^{-1}$
arc ctg	$\cot^{-1}$
arc sec	$\sec^{-1}$
arc cosec	$\csc^{-1}$
arc sh	$\sinh^{-1}$
arc ch	$\cosh^{-1}$
arc th	$\tanh^{-1}$
arc cth	$\coth^{-1}$
arc sch	sech^{-1}
arc csch	csch^{-1}
rot	curl
lg	log

INVESTIGATION OF MIXERS OF THE COMBUSTION CHAMBER OF GAS AND STEAM-GAS TURBINES

I. B. Palatinik and D. Zh. Temirbayev

Results are given of the calculation and experimental investigation of models of the mixer of the combustion chamber of gas and steam-gas turbines.

In different technical devices and, in particular, in combustion chambers of gas and steam-gas turbines we run into the necessity of lowering the temperature of products of combustion to the required level (usually 2-3 times) where the distribution of speed, temperature and so on in the obtained flow should be sufficiently uniform. One of the procedures providing intense mixing is the introduction through the lateral walls of the chamber of a system of transverse streams evenly mixed with the flow (Fig. 1).

In view of the complexity of the examined process of displacement at the present time we usually proceed along the lines of experimental investigation of different constructive and condition parameters and further "finishing" of the mixer. Such a way, which is very time consuming, gives a solution only for the given concrete mixer. In connection with this there is considerable interest in the creation of a rational method of calculation which allows precalculating results of mixing in mixers of the stream type.

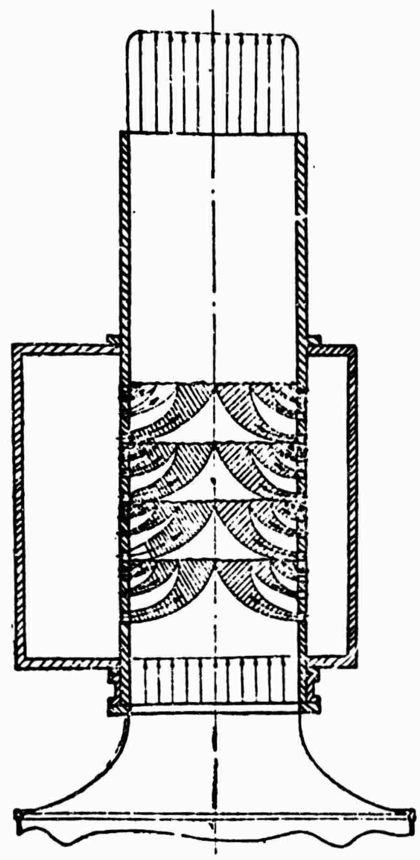

Fig. 1. Diagram of a mixer of the stream type.

Given in this article are results of the calculation and experimental investigation of models of mixing chambers. Assumed as the basis of calculation of such models are data on the propagation of a single stream and a system of streams in transverse uniform flow obtained in the works of Yu. V. Ivanov [1, 3].

The essence of these data in short is reduced to the following. With the flowing of a circular stream whose density is ρ_1, and speed u_1, into the transverse flow with values of density ρ_2 and speed u_2 (Fig. 2), the equation of the trajectory of the stream has the form

$$\frac{y}{d} = \left(\frac{\rho_2 u_2^2}{\rho_1 u_1^2}\right)^{\frac{1}{3}} \left(\frac{x}{d}\right)^3 - \frac{x}{d} \operatorname{tg}(\alpha - 90), \tag{1}$$

where α is the angle between the initial direction of the speed in the stream and flow (on Fig. 2 $\alpha = 90^\circ$) and d is the diameter of the stream at the outlet of the nozzle.

The relative depth of penetration of the stream into flow h is determined by the formula

$$\frac{h}{d} = K_s \sqrt{\frac{\rho_1 u_1^2}{\rho_2 u_2^2}} \cdot \sin\alpha, \tag{2}$$

where K_s is the dimensionless experimental coefficient whose values are given in works [1, 3].

Furthermore, in the calculation there is used experimental fact established in work [2] that at the depth of penetration the effective

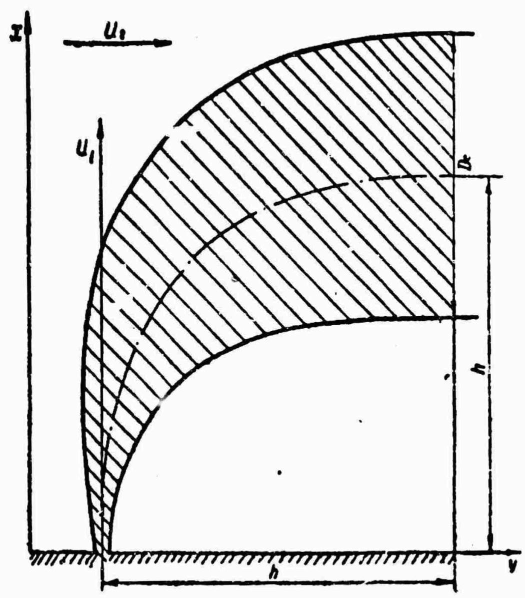

Fig. 2. Diagram of propagation of the stream in a transverse uniform flow.

diameter of the stream is equal approximately to 0.75 h,

$$D_{эфф} = 0{,}75h. \qquad (3)$$

On the basis of the indicated experimental data calculation was conducted of the model of the mixing chamber. The investigated model was calculated with the following condition parameters: mixing chamber is cylindrical, ∅ = 2[illegible]0 mm, speed of combustion products at the entrance into the mixer is equal to u_{BX} = 10 m/s, temperature t_{BX} = 600°C, flow rate of combustion products G_{BX} = 0.2 kg/s.[1] It was further assumed that the flow rate of air coolant exceeds three times the flow rate of combustion G = 0.6 kg/s.

With calculation of the model of the mixer it was assumed that the air introduced for cooling is evenly distributed between four groups of holes, containing by fours, series in each group. A direct calculation of the quantity and dimensions of the holes in each series was conducted by the diagram shown in work [1]. With this (and this is very significant to us) it was considered that the introduction of a definite part of cold air into one group of holes increases the momentum of flow of combustion products in front of the following group (quantity $\rho_2 u_2^2$ in formula 2). Thus during transition from one group

[1]During investigation of the model it is assumed that the process of mixing on account of the presence in the chamber of well developed mixing does not depend on the Reynolds number of the flow, and thus, results of the investigation can be transferred to chambers of other dimensions.

Table 1

Group	I		II		III		IV	
Series	Number of holes	d, mm	Number of holes	d, mm	Number of holes	d, mm	Number of holes	d, mm
1	18	10	9	14	6	17,5	4	21,5
2	100	4,1	45	6,1	30	7,5	20	9,2
3	78	2,3	40	3,2	26	4	18	4,8
4	400	1,3	194	1,9	134	2,3	90	2,8
	t=390°C u=12,6 m/s		t=293°C u=14,7 m/s		t=228°C u=17,2 m/s		t=192°C u=20 m/s	

of holes to the other, it is necessary to consider change in quantity $\rho_2 u_2^2$. In other respects the calculation is reduced to simple arithmetical operations [1]. Results of the calculation of the quantity and dimensions of the holes are given in Table 1.[1]

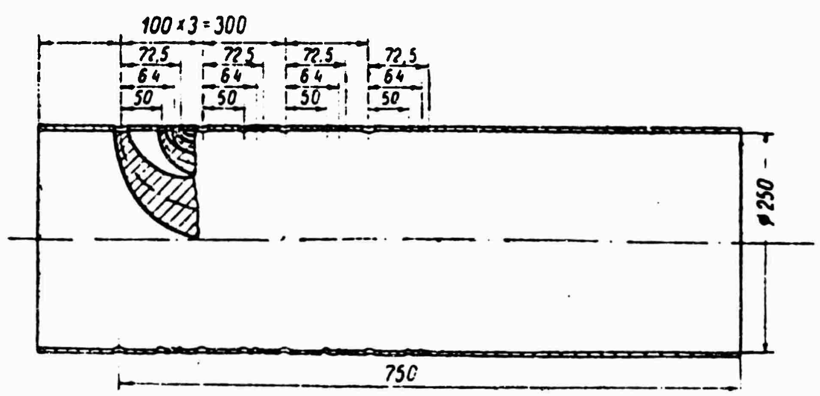

Fig. 3. Diagram of the model of mixing chamber.

Figure 3 shows a diagram of the model of the mixing chamber. As can be seen from the figure, the whole mixer has a length of 750 mm, which consists of 3 gauges of mixing chamber. The holes for the entrance of air coolant occupy half of the length of the mixer, and the remaining part is intended for the smoothing of perturbations

[1]Shown in the lower lines Table 1 are values of temperature and speed which were obtained as a result of mixing the air with the flow of combustion products after each group of holes.

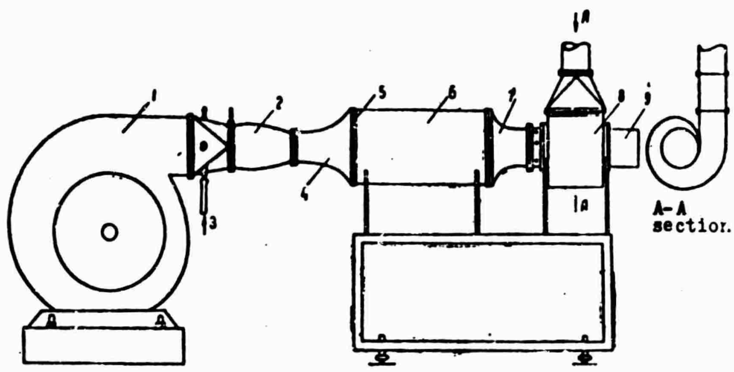

Fig. 4. Diagram of an experimental installation. 1 — fan; 2 — combustion chamber; 3 — combustible gas feed; 4 — curvilinear diffuser; 5 — levelling screen; 6 — damping chamber; 7 — nozzle; 8 — scroll feed; 9 — mixing chamber.

appearing during mixing.

For the purpose of checking the method of calculation used there was developed an experimental installation depicted on Fig. 4. The basic flow was supplied by a centrifugal fan of the [VD-6] (ВД-6) type. Further the flow of air was heated in the combustion chamber operating on natural gas and then through a diffuser, damping chamber and convergent nozzle was fed to the mixing chamber. Cold air for mixing was supplied from a separate fan (not shown on the diagram) with the help of a scroll distributor.

In the calculation of the model of the mixing chamber it was assumed that the distribution of speed and temperature in the flow of products of combustion at the entrance into mixer was uniform. For the production of such flow special measures were taken. Thus both the transition nozzle and diffuser were made curvilinear on recommendation of the work [4]. All these measures permitted obtaining the initial flow, the distribution of speed and temperature in which is shown in Figs. 5 and 6.

As calculations showed, the ratio of temperature average along

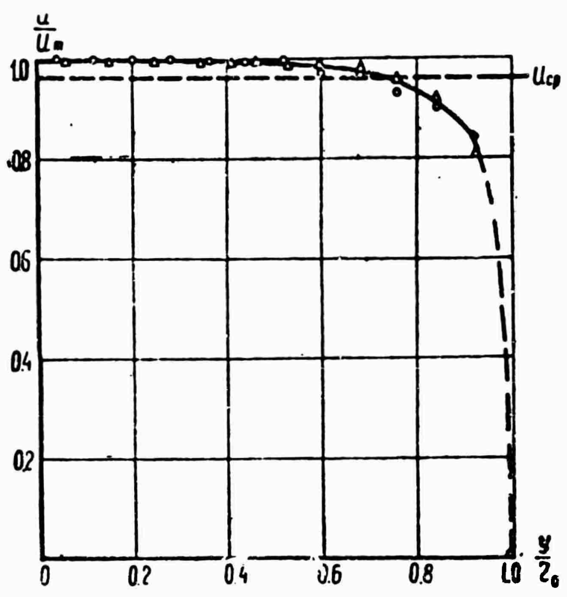

Fig. 5. Distribution of speed at the entrance into the mixing chamber.

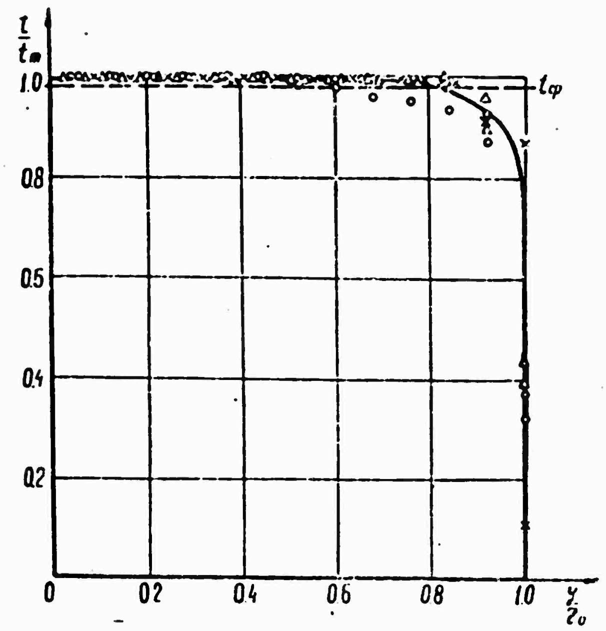

Fig. 6. Distribution of temperature at inlet of the mixing chamber.

cross section to the maximum is ≈0.98, and of the speed, ≈0.96, which, in our opinion, is fully acceptable.

The feed of air coolant was accomplished with the help of a scroll spiral chamber, carried out on recommendations of V. N. Taliyev [5]. As measurements showed, such a feed provides constant speed of air inflow in holes of the mixing chamber, where deviation from the mean value does not exceed 2-3%.

All measurements of speed here and subsequently were conducted by tubes of full and static head connected to a differential micromanometer of the [MMN] (MMH) type with a minimum scale value of 0.2 mm H_2O. Thus the error in the measurement of speed did not exceed ≈5%.

Regarding measurements of temperature, they were conducted with help of a differential thermocouple nichrome-constantan connected to a potentiometer of the [PP] (ПП) type with a minimum scale value of 0.1 mV, which for the given thermocouple makes up the difference in

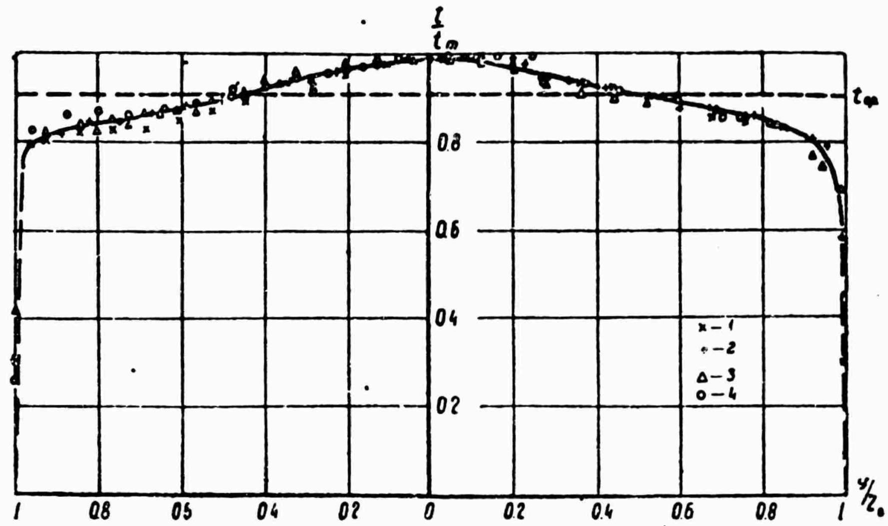

Fig. 7. Distribution of temperature on the radius at the exit of the mixing chamber. Groups of holes operating: 1 — one; 2 — two; 3 — three; 4 — all four.

temperatures of $\approx 2^{\circ}$. Thus the error in measurement of temperature did not exceed 1.5% for all its values.

During experimental investigation of the model of the mixing chamber first of all there were checked results of mixing with the inclusion of each group of holes separately. For this in the beginning there was left open only the first group of holes; then operating conditions were set of the mixer in accordance with the calculation of the first group (Table 1) and was measured the distribution of speed and temperature at the exit from the mixing chamber. Analogous measurements were conducted during operation of two, three and all four groups of holes of the mixer. The thus measured distribution of exit temperature of the mixer is shown in Fig. 7.

As calculations showed, the ratio of the average temperature on the cross section of the chamber to the maximum is 0.92-0.93, which gives a deviation of 7-8% from the mean value. Tests during the inclusion of separate groups of holes give similar results.

As one can see from Fig. 7, the irregularity of the temperature

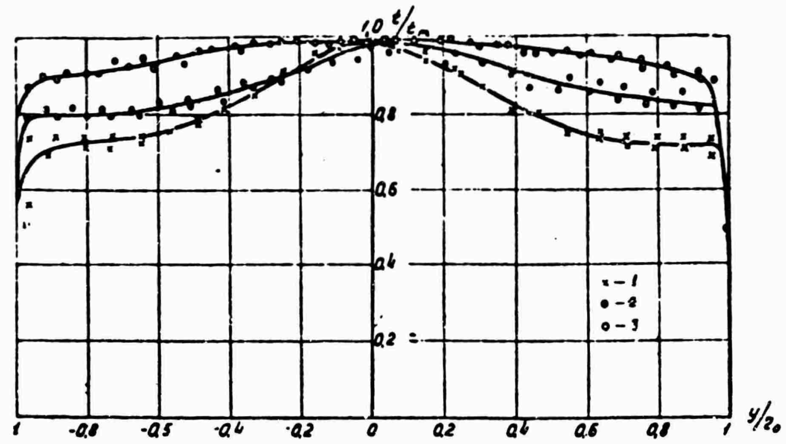

Fig. 8. Distribution of temperature in the cross section of the mixer at different distances from the last series of holes. The ratio l/d is equal to: 1 — 0.7; 2 — 1; 3 — 1.5-2.0.

field (the value characterizing the degree of mixing of introduced streams with the flow) is connected with the continuous increase in temperature from the periphery to the center. At the outlet of the mixer there are not any sharp oscillations of temperature; however, the central regions are found to be overheated with respect to the peripheral.

It is natural that the indicated irregularity should increase with an approach to the last holes of the mixer. This was checked experimentally. Figure 8 shows the distribution of temperature on the cross section of the mixer at different distances from the last series of holes. As can be seen from the figure, in direct proximity from the last series of the holes there is considerable irregularity which rapidly decreases along the length of the chamber.

In our opinion, this occurs because of the following. With calculation it is assumed that the introduced stream brings its whole momentum and heat content into a definite place and is mixed there with the flow. In reality each stream is mixed partially with the

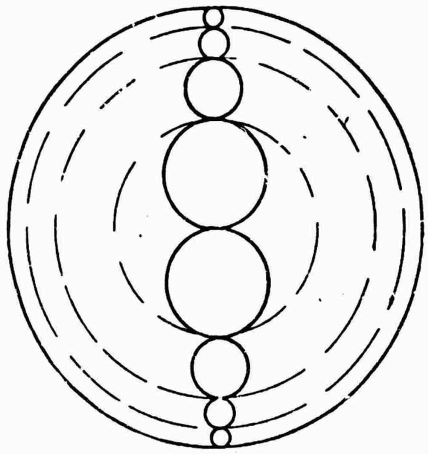

Fig. 9. Diagram of the location of streams in the cross section of the mixer with a four-row arrangement of the holes.

flow and up to a maximum penetration into the flow. Apparently, this is especially considerable for streams of the greatest dimensions called upon to cool the central region, as a result of which this region is found to be overheated.

From a qualitative side it is clear that for a decrease in overheating of the cental regions it is necessary to direct into the center a greater part of the consumption of cold air than follows from the principle of uniform feed per unit area of a section of the chamber.

The absence at present of sufficiently detailed data on the mixing of the stream and system of streams with the transverse flow does not enable producing recomputation of the distribution of cold air in the section of the mixer. At the same time such a redistribution can be conducted on the basis of qualitative considerations.

Figure 9 gives a diagram of the location of the holes with a four-row supply of air in the section of the mixer in the fourth group of holes (Table 1). As can be seen from the figure, for the part of the smallest holes of the fourth row a relatively small region near the wall of the mixer is necessary. Furthermore, this region is partially cooled by streams of other rows of holes passing through it.

In connection with this it appears possible to give up holes of the fourth row and to redistribute the remaining air between the remaining rows of holes. For an experimental check of this assumption by analogy with scheme of calculation described earlier, calculation

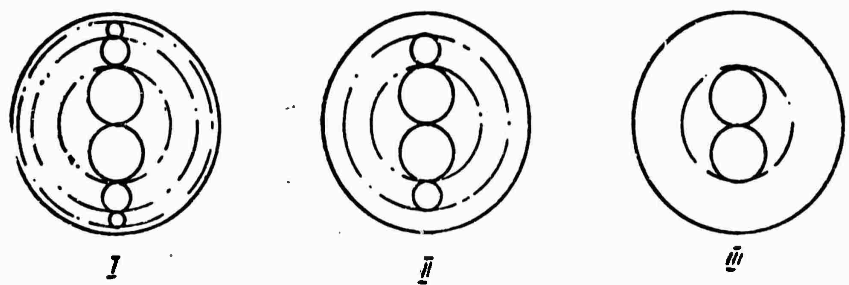

Fig. 10. Diagram of the arrangement of the streams in the cross section of the mixer. Arrangement of holes: I — three-row; II — two-row; III — single-row.

was conducted for a model of a mixing chamber in which the consumption of cooling air is five times less than the consumption of products of combustion: $G_c = 0.04$ kg/s, where in the section of the chamber air was fed only into 3 rows of holes of the first group.

An experimental investigation of this chamber (results of it are given below) showed that at a distance of 1.5 gauge from the last holes of the mixer the uniformity of the temperature field is somewhat improved as compared to the four-row arrangement of the streams in the section of the chamber.

Table 2

Chamber	Three-row		Two-row		Single-row	
No. of series	Number of holes	d, mm	Number of holes	d, mm	Number of holes	d, mm
I	6	9	8	8,8	10	14
II	22	5	35	4,5	—	—
III	56	2,4	—	—	—	—

It was natural to try to reject further the third and second series of holes consecutively. Thus, there were conducted calculations and an experimental investigation for mixers with a small ratio of consumption of air coolant and products of combustion (1/5) into whose section were fed the 3, 2 and 1 rows of streams respectively, all of these streams being grouped around the center of the mixer, and the

peripheral region in the calculation remained free. A diagram of the arrangement of the streams is shown in Fig. 10. The dimensions and quantity of holes in different rows of the investigated chambers are given in Table 2.

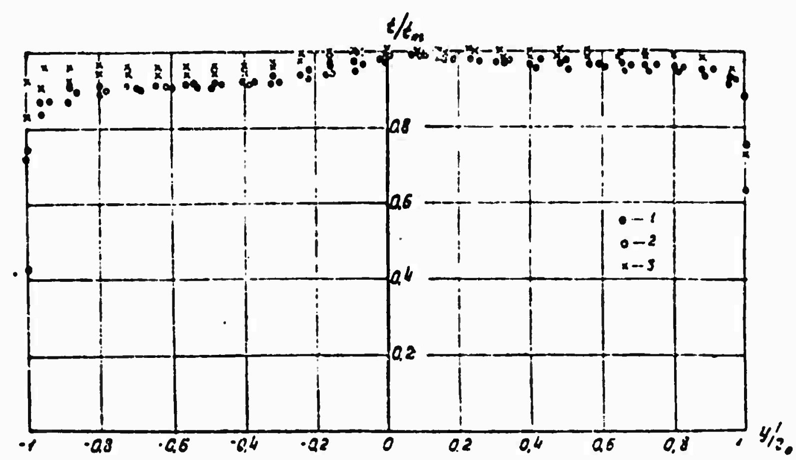

Fig. 11. Distribution of temperature in the cross section of the mixer with a small ratio of consumptions with a different quantity of series of holes. Arrangement of holes: 1 — three-row; 2 — two-row; 3 — single-row.

Figure 11 gives data of tests of these chambers. As can be seen from the figure, with a single-row supply of streams into the section of the chamber there will be attained the best uniformity of the temperature field at the outlet of the mixer. Deviation of the mean temperature along the section from the maximum does not exceed 3-4% at a distance of 1.5 gauges of the chamber from the last holes.

An analogous investigation was conducted for mixing chambers with a large ratio of consumptions of air coolant and products of combustion (3:1). In this case it was assumed that the air coolant is introduced into the 4 groups of holes. However, in contrast to the preceding, the air in each group was fed only into one row of holes in such a manner that the stream were grouped around the center of the section of the mixing chamber.

Let us note one circumstance typical for mixers with a large ratio of consumptions of air coolant and products of combustion. The fact is that the introduction of a sonsiderable quantity of air coolant leads to a noticeable increase in the momentum of the flow. Thus the quantity $\rho_2 u_2^2$ in formulas (1) and (2) becomes indefinite.

In this case, as is recommended in work [6], for the quantity $\rho_2 u_2^2$ in the flow one should take the value of flux density of momentum which is established as a result of the mixing of streams of the given series of holes with the flow, i.e., the value $\rho_2 u_2^2$ after the given series of holes. The quantity and dimensions of holes for the model with a large ratio of consumptions of the mixer consisted of the following:

I group — 18 holes, d = 12.5 mm;
II group — 11 holes, d = 22.5 mm;
III group — 8 holes, d = 27.0 mm;
IV group — 5 holes, d = 33.0 mm;

Figure 12 shows the distribution of temperature at the outlet of the mixing chamber at a distance of 1.5 gauges from the last holes. And in this case the direction from the mean temperature along the section does not exceed 3-4%.

The improvement in uniformity of the temperature field at the outlet of the mixer, obtained with a single-row supply of streams, seems regular to us, since in spite of the peripheral part of the flow supposedly left in this case without cooling, in reality it is intensively cooled by streams proceeding into the center. Besides the best mixing, a single-row supply of streams in the section of the chamber results in, of course, considerable design simplifications.

Thus the conducted investigations permit considering that the

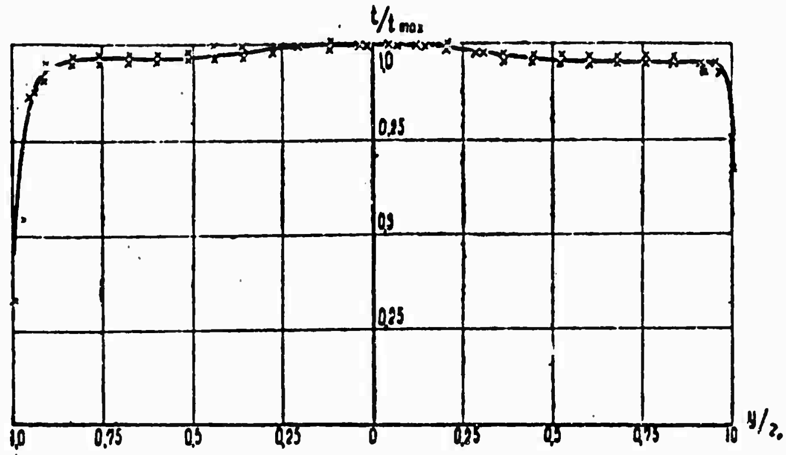

Fig. 12. Distribution of temperature in the cross section of the mixer with a large ratio of consumptions with single-row arrangement of the holes.

applied method of calculation of mixing chambers permits obtaining a flow the distribution of parameters in which it is possible to consider uniform with sufficient accuracy for practical purposes and can be confidently recommended for calculation of mixers of the stream type.

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